Predicting the Life Cycle Costs of Structures Based on Accelerated Corrosion Testing: A Framework for Incorporating Reliability Concepts

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ABSTRACT

In order for Bridge Management Systems (BMS) to be effective, they must be based on a reliable, statistically sound means for predicting service life for the variable conditions and structures that are present on the system. To make sensible life cycle cost decisions in design and construction, bridge engineers must be able to account for distress phenomena such as corrosion, and to assess the impact of durability strategies.

In recent years various corrosion protection systems have been evaluated. Most evaluations involve accelerated laboratory testing, and, in some instances, limited field verification. In general, these evaluations have considered only a few samples and somewhat limited test conditions, providing a database that is inadequate for reliable life prediction for the wide range of real world structural conditions and applications. Thus, it is important how test data is analyzed and extrapolated with respect to a real structure and the bridge system as a whole.

This paper will present a methodology for incorporating statistical reliability considerations into corrosion service life prediction and life cycle cost analysis that was developed as part of a Federal Highway Administration (FHWA) study of corrosion resistant reinforcement. This approach gives the engineer the ability to statistically consider different material, environmental, structural, and corrosion protection factors in computing the life cycle costs, and is applicable to any corrosion protection system. Its application will be demonstrated using corrosion performance data and service models from the FHWA study.

KEYWORDS: Epoxy-Coated Reinforcement, Life Cycle Costing, Rehabilitation, Reliability, Repair, Risk, Service Life

INTRODUCTION

Durability

Assuring durable, long lasting structures is a major focus of design, and thus, protecting against corrosion of steel reinforcement in concrete is a major consideration in achieving this objective. Extensive research has led to the development and improvement of a myriad of corrosion protection strategies to mitigate the ravaging effects of corrosion. Most of this research involves accelerated testing in the laboratory, and in some instances, verification with limited long-term field observations. In general, these evaluations have considered only a few samples and limited test conditions, providing a database that is inadequate for reliable life prediction for the wide range of real world structural conditions and applications.

Practitioners, on the other hand, need a reliable, statistically sound basis for predicting service life for their variable conditions and structures in order to make sensible life cycle cost decisions in design and construction. With an abundance of alternatives, and contradictory research and marketing hype, a designer has a formidable task in selecting a corrosion protection system for a structure.

Economics of Corrosion

While most corrosion research has focused on system effectiveness, performance is not the only factor to be considered in choosing a protection strategy; economics is equally important. Achieving an optimal balance between performance and cost is the key to sound decision-making.

The cost of corrosion-induced damage on reinforced concrete structures can be very high. The costs associated with repair and rehabilitation, and with disruption to the public's use of the facility, often exceed the original construction cost. To avoid (or delay) costly maintenance, repair and rehabilitation, and to maintain structural integrity in a corrosive environment, some means of corrosion protection is usually warranted.

In addressing this decision, several questions come to mind:

- How does one decide what protection strategy to use?
- What will it cost and is it worth it?
- How does one compare different technologies and strategies?
- How can what is measured in the laboratory be translated into what actually occurs in the field?
- How can service life be predicted with any level of confidence?
- How can a designer assess the economic impact of certain design and construction decisions and actions?

RELIABILITY-BASED LIFE CYCLE COSTING

Reliability-Based Life Cycle Cost Analysis (RB-LCCA) is a powerful decision-support tool and can be used to address these questions.

This paper introduces a simplified methodology for incorporating statistical reliability considerations into corrosion service life prediction and life cycle cost analysis. This methodology gives the engineer the ability to statistically consider different material, environmental, structural, and corrosion protection factors in computing the life cycle costs.

Repair to concrete structures due to corrosion-induced delamination or spalling only occurs when there has been sufficient damage. It is important to consider how in-concrete corrosion test data is analyzed with respect to performance of a real structure.

The methodology presented here is applicable to all corrosion protection systems, and will be used to demonstrate the benefit—in life cycle cost terms—of quality control during construction and preventive maintenance during the life of a structure.

What Is Reliability-Based Life Cycle Cost Analysis (RB-LCCA)?

Section 303 of the Quality Improvement of the National Highway System (NHS) Designation Act defines Life Cycle Cost Analysis (LCCA) as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment." Life cycle costing has been used for decision-making since the nineteenth century; however, it is receiving increasing attention as an investment decision tool by transportation agencies.

Reliability-Based (Probabilistic) vs. Deterministic Analysis

Traditionally, life cycle cost analysis has been done without regard for variability of parameters. Best guesses are commonly used for input values, yielding a single life cycle cost result. Unfortunately, while this approach is simple and straightforward, it fails to recognize the significant effect the inherent variability input parameters can have on structure performance and analysis. In a LCCA, these uncertainties should be considered.

Variability and uncertainty result from assumptions, estimates, and projections used as inputs for the LCCA. These inputs vary both within a structure and from project to project. With respect to corrosion protection of reinforced concrete structures, variability can come from many areas, including:

- Materials—concrete is non-homogeneous material. Strength, permeability, resistivity and air content can vary significantly for a given concrete mix.
- Environmental Exposure—chloride exposure, temperature, moisture content directly influence corrosion rate and chloride ingress.
- Design—size and spacing of steel, concrete cover, and electrical continuity of steel may affect both cost and performance.
- Structural Load—stress, dynamic loading and vibration, and hydrostatic pressure from wave action or tire pressure can indirectly influence deterioration rates.
- Construction factors—consolidation, curing, temperature/moisture control, and damage.
- Maintenance—assumptions must be made regarding future maintenance activities, and their timing and effectiveness. Practices vary considerably in frequency and quality.
- Costing—construction and rehabilitation costs can be extremely variable. Cost estimating becomes more difficult, the further in the future it is. Our analysis challenge is further complicated by our inability to accurately forecast the timing of future actions.
- Quality can also be variable. Some contractors provide quality far above the levels specified, while others build the bare minimum to meet specifications.

Reliability and Risk Analysis

Reliability (or its converse, risk) is based on recognition of uncertainty and our inability to accurately predict the future. The American Association of State Highway and Transportation Officials (AASHTO) has defined reliability as the probability that any

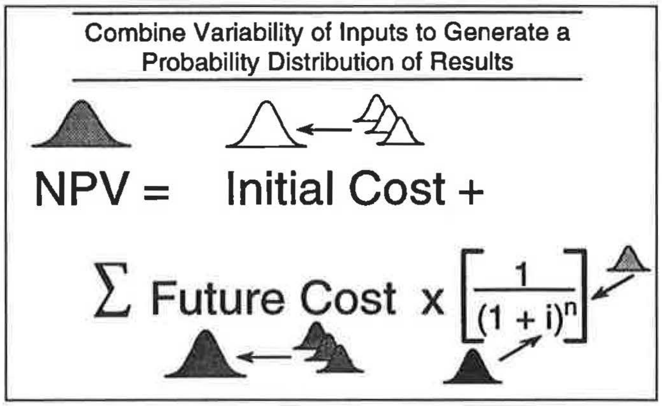


Figure 1: Life cycle costing should consider the variability of all major input parameters.

particular type of distress will remain below or within the permissible level during the design life (*1*). RB-LCCA is a technique combining traditional life cycle cost procedures with risk analysis. This approach makes use of statistical probability distributions to characterize uncertainty of variables (Figure 1).

Selection of an appropriate level of reliability for a given structure depends on projected usage and the consequences (risk) associated with corrosion-related distress. For a given facility, the optimum level of reliability represents the lowest overall life cycle cost (i.e., the combination of initial and future costs).

Zero Defects vs. Law of Diminishing Returns

Everyone would like to have a 100 percent guarantee of performance on anything that they buy. While this is certainly a worthy objective, it is usually accompanied with a not-so-attractive price tag. For example, in corrosion protection, one could use titanium reinforcement and provide an extremely high level of durability and protection; however, the high initial cost of titanium is prohibitive and beyond consideration in most cases. Nuclear power plants are other examples where very high levels of reliability are demanded to assure public safety. But, as these projects repeatedly have demonstrated, construction costs can soar when very high levels of reliability are specified. Figure 2 illustrates the concept of selecting an optimum level of reliability for a structure.

It is important that equivalent levels of reliability be used when evaluating alternatives. For example, comparing one protection strategy based on a service life estimate for a 90 percent level of reliability to another based on mean service life (50 percent reliability) will yield an erroneous life cycle cost analysis and is inappropriate. As shown in the example of Figure 3, different reliability levels will result in different predicted service life for the same protection system.

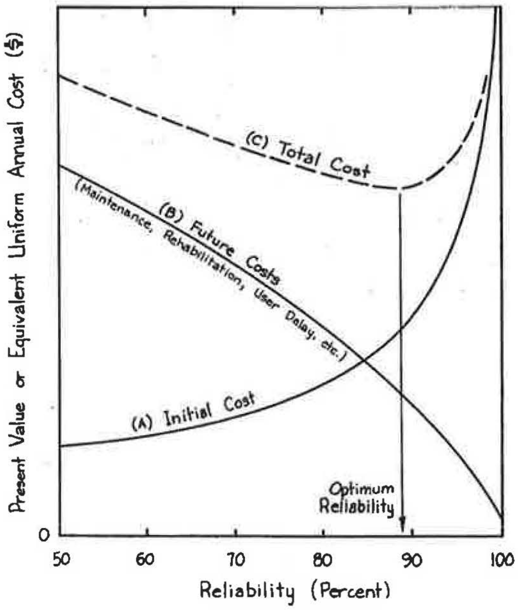


Figure 2: Identifying optimum reliability level for a given facility. (Source: Reference 2)

Why Reliability-Based Life Cycle Cost Analysis?

RB-LCCA leads to more informed and better decisions. Due to project peculiarities and differences in protection systems, it is one of the few ways to meaningfully compare alternatives on an "Apples to Apples" basis. In concept, proper RB-LCCA will identify the alternative that will give the highest level of service at the lowest overall cost, thereby maximizing benefit and return on investment.

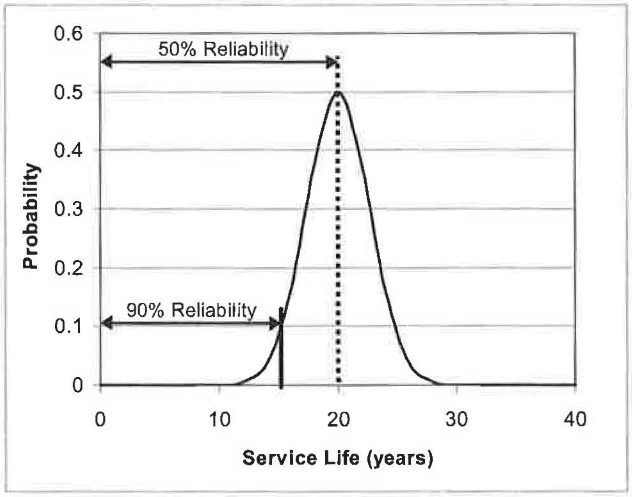


Figure 3: Choice of reliability level influences predicted service life.

Incorporating risk analysis techniques should reduce risk of premature failure and increase overall structure reliability. RB-LCCA provides a quantitative means to assess the impact of design, construction, and maintenance decisions. Finally, it is a tool that facilitates consensus building among stakeholders through better understanding of performance and cost tradeoffs.

LIFE CYCLE COST ANALYSIS METHODOLOGY

Historical Approach in Transportation

Although LCCA is commonplace in other fields, in transportation, investment decisions have historically been made on the basis of lowest initial cost, usually with no consideration of user impacts.

Where life cycle cost concepts have been considered, they are generally derived from engineering judgement based on personal experience and anecdotal evidence. As previously noted, life cycle cost analyses have traditionally been deterministic with "one size fits all" general solutions that are applied to most, if not all, situations.

LCC Analysis Needs

One of the first steps in a LCCA is to determine the desired analysis period (i.e., the time horizon to be studied). The analysis period should be sufficiently long to reflect long-term differences associated with feasible alternatives. For bridges: 75 to 100 years is typical; for parking structures: a somewhat shorter analysis period of 30 to 50 years is common.

Next, the terminal serviceability level needs to be defined. Terminal serviceability (also referred to as end-of-functional-service-life) is the maximum level of distress that will be permitted prior to major repair or rehabilitation of the structure. To a large extent, terminal serviceability will depend on the functional requirements (e.g., structural capacity, aesthetics, smooth ride, etc.) of the structure.

For many agencies, delamination of 10 percent to 20 percent of a bridge deck area constitutes terminal serviceability. Fitch et al. in a study of bridge service life found that this level varies from engineer to engineer, and agency to agency (*2*).

As previously mentioned, the designer has many choices (and combinations) for protecting a reinforced concrete structure from corrosion. Table 1 lists some of the more common options.

PREDICTING PERFORMANCE AND SERVICE LIFE

Estimating the future service life of a structure (and the life extension provided by a corrosion protection system) is perhaps the most subjective aspect for life cycle cost analysis of corrosion protection systems, but also, the most important. The time-to-repair is the most critical decision-making step in selecting corrosion protection strategies and will usually have a major impact on life cycle cost. This task is made difficult by a

Table 1: Common Corrosion Protection Strategies

Type of Protection System	*Description*
Reinforcement materials & coatings	Epoxy coating Galvanized rebar Stainless steel rebar and cladding Composites
Concrete additives & mix design	Inhibitors High performance concrete Low w/c ratio Microsilica
Surface sealers, membranes & overlays	Silanes/siloxanes Latex modified Dense and microsilica-enhanced concrete overlays Waterproof membranes
Electro-chemical processes	Cathodic protection Electro-chemical chloride removal
Maintenance practices	Non-corrosive deicing chemicals Crack repair Deck washing Drainage and joint system upkeep
Design details	Cover Deck thickness Drainage joints Mat-to-mat separation
Construction practices	Curing Temperature control Specification enforcement
Combinations of the above alternatives	

limited database and short history for most alternatives. Oftentimes, it has been prone to gross oversimplification and generalization.

To predict future service life with any accuracy, important determinants of performance for any given protection system need to be identified. This includes determining those factors which account for the greatest variability in service life performance, and developing deterioration models based on those key variables.

For example, a recent research study sponsored by the Federal Highway Administration (FHWA) has shown that the performance of epoxy-coated reinforcement will be heavily influenced by chloride diffusion rates, coating damage, concrete cracking, and electrical continuity of steel (*3*). Research by Bremner indicates that the service life of High Performance Concrete (HPC) will be dependent on chloride diffusion rate, concrete cracking, consolidation, curing, and cover (*4*).

One must utilize either multiple corrosion degradation models, which account for commonly expected combinations of key performance factors, or a model that incorporates the significant parameters. It is not usually sufficient to (as is commonly done in corrosion studies) predict service life on the basis of one factor (such as chloride diffusion), unless that parameter can be shown to be the only one to have a statistically significant impact on performance. This is rarely the case for any protection system.

Accelerated testing in the laboratory can be used to evaluate the impact of key variables and help define the probability distributions necessary to model performance. Wiss, Janney, Elstner Associates, in the aforementioned FHWA study, investigated the effect of adhesion, coating damage, chloride diffusion, fabrication, and uncoated steel cathode areas on the performance of epoxy-coated reinforcement (*3*). Test conditions were devised to represent commonly encountered conditions in the field and are shown in Table 2. Values used were based upon estimates obtained from currently available field data for structures containing epoxy-coated reinforcing bars.

Decks contain concrete areas that are cracked and uncracked, and epoxy-coated steel that has significant damage on some bars and minor damage on others. The degree to which each condition exists will influence the overall performance of the structure.

Initiation of Corrosion

Based upon diffusion calculations and data from laboratory studies, high-quality uncracked concrete with proper cover should not reach corrosion initiation for many

Table 2: WJE/FHWA Study Test Conditions

		Concrete	
		Uncracked	Cracked
Reinforcement	Top mat-only coated Bottom mat-black	Minor damage (0.004%)	Minor damage (0.004%)
		Significant damage (0.5%)	Significant damage (0.5%)
	Both mats coated	Minor damage (0.004%)	Minor damage (0.004%)
		Significant damage (0.5%)	Significant damage (0.5%)

years after construction. However, not all of the deck reaches this initiation state at the same time. Variances in salt accumulation, in concrete cover and in microenvironments. Thus, use of statistical estimates for time-to-initiation of corrosion is appropriate.

For simplicity, assuming the time-to-initiation is normally distributed, one can calculate the time for an uncracked deck to reach corrosion initiation. A hypothetical normal probability distribution for the time to reach the chloride initiation is shown in Figure 4.

Similarly, not all of a concrete deck is uncracked. Assuming that a percentage of the deck is influenced by the presence of cracks, the time-to-initiation for a cracked section of a deck is more rapid. One can combine the probability distributions for cracked and uncracked concrete into a cumulative probability distribution for initiation of corrosion. From this data, one can then estimate the time that it takes to reach corrosion initiation on a specified area of the deck corresponding to the maximum acceptable level of distress.

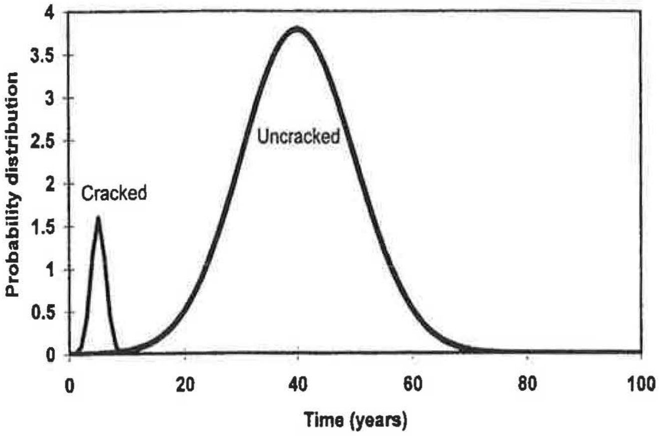


Figure 4: Probability distribution for initiation of corrosion of black bars in cracked and uncracked concrete deck.

Time to Delamination

Once corrosion has initiated, it takes time before delaminations occur. Assuming again that the time-from-initiation to delamination for both cracked and uncracked decks is normally distributed, one can calculate the overall time-to-delamination.

Table 3 lists some sample values for these statistical parameters. Based on this data, Figure 5 shows the cumulative probability distribution for time-to-delamination for a deck with 5 percent cracked and 95 percent uncracked areas. From this figure, 10 percent of the deck will be delaminated after 30 years and 20 percent after 35 years.

Table 3: Sample Probability Distribution Data

	Parameter	Mean	Standard Deviation
Black Bar	Time-to-corrosion initiation--uncracked	40	10
	Time-to-corrosion initiation—cracked	5	1.25
	Time-to-delamination—cracked & uncracked	5	1.25
Epoxy-Coated Bars	Time-to-corrosion initiation—ECR minor damage	25	6.25
	Time-to-corrosion initiation—ECR significant damage	10	2.5
	Time-to-delamination—cracked & uncracked	5	1.25

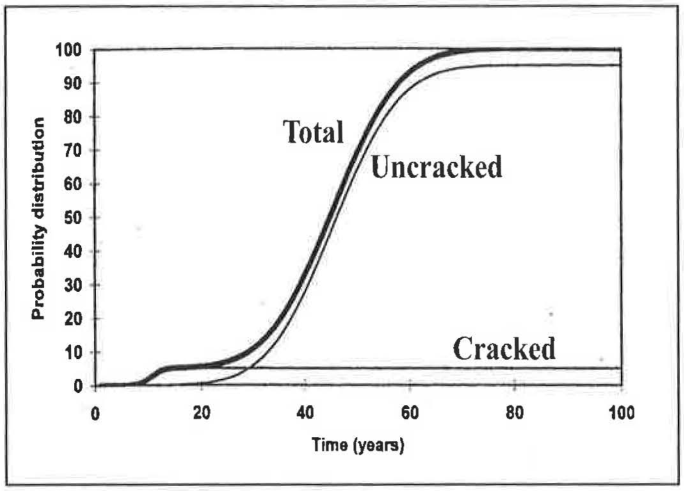


Figure 5: Cumulative distribution for delamination of deck with black bars.

When considering a deck constructed with epoxy-coated bars, one has to estimate the quantity of deck under the various conditions of cracked and uncracked concrete, and with minor and significant coating damage. Using the sample distribution data in Table 3 and assuming that the deck has 95 percent uncracked and 5 percent cracked areas, and that 85 percent of the steel has minor damage and 15 percent significant damage, the following conditions can be estimated:

- Uncracked concrete, minor coating damage—80.75 percent of total deck area
- Uncracked concrete, significant coating damage—14.25 percent of total deck area
- Cracked concrete, minor coating damage—4.25 percent of total deck area
- Cracked concrete, significant coating damage—0.75 percent of total area.

Using these data, one can plot the cumulative probability distribution for delamination occurring to the structure as shown in Figure 6.

Estimation of Times to Repair

It is possible to estimate the time period necessary to reach a certain terminal serviceability level (in this case based on the amount of deck delamination.) Table 4 shows the estimated time for various amounts of delamination to occur based on the example used in this discussion.

On a more important structure, such as a freeway bridge with high traffic volume, a designer might specify a higher terminal serviceability level—allowing only 2.5 percent delamination prior to repair. Consequently, the time-to-repair may substantially vary from structure to structure depending on what the designer specifies as the terminal serviceability level. As a result, the benefit of using a corrosion protection system may also. The selection of the protection system may be significantly

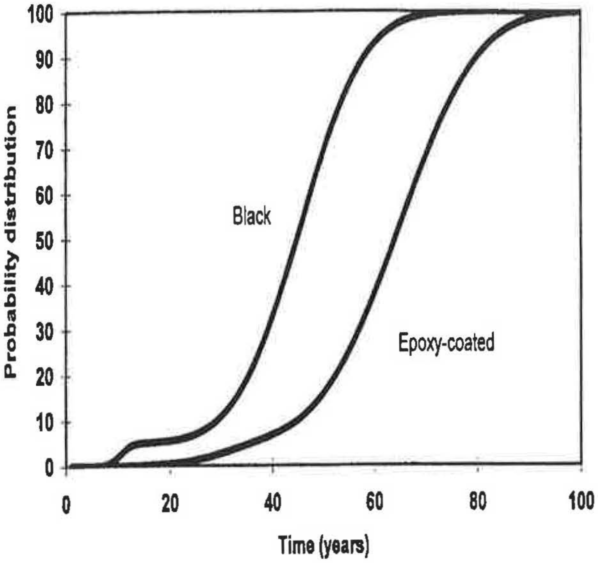


Figure 6: Cumulative distribution for delamination of concrete decks containing black and epoxy-coated bars.

Table 4: Estimated Time-to-Repair

Amount of delamination, %	Black bars, years	Top-mat epoxy-coated bars years
1	8	20
2.5	9	27
5	14	33
10	28	42
20	35	49
30	38	54

influenced by the performance requirements of the structure. Therefore, the projected time-to-repair is a critical input to RB-LCCA of corrosion protection strategies.

BENEFITS OF QUALITY

It is now possible to consider what would happen if large defects in the epoxy-coated bars were eliminated through strict quality control measures or cracks in bridge decks containing either epoxy-coated or black bars were eliminated or repaired, as shown in Table 5.

LCCA can be used to quantitatively assess the benefits of improved quality of materials and construction. Typically, higher quality leads to two benefits which reduce overall life cycle cost—extended service life and reduced variability.

By comparing the added estimated cost to achieve the higher quality level to the projected performance gain, it is possible to determine whether a specific action is warranted. Using the data in Table 5 and the life cycle cost analysis example in Appendix A, simply repairing the cracks and minimizing coating damage, a deck's life could be extended 8 years (for a terminal serviceability of 10 percent delamination). In terms of

Table 5: Estimated Time-to-Repair Using Different Construction Strategies

Predicted amount of delamination, %	Black bars, years		Top-mat epoxy-coated bars, top-mat only, years			
	No repair of cracks in concrete	Repair of cracks in concrete	No repair of cracks and poor quality control for epoxy-coated bars	Repairing cracks in concrete	Repairing holes in epoxy through on-site quality control	Repairing cracks in concrete and repairing holes in epoxy
1	8	21	20	32	24	37
2.5	9	25	27	37	29	42
5	14	28	33	41	36	45
10	28	32	42	46	46	50
20	35	36	49	50	53	55
30	38	39	54	56	57	58

life cycle costs, this reduces the net present value for the given alternative and example by $4.44 per square foot.

Similarly, LCCA can be used to assess the effectiveness and determine the optimum timing for preventative maintenance.

REHABILITATION AND REPAIR

What, when, and how? Another key input for LCCA of corrosion protection systems is the rehabilitation and repair strategy that is planned once the structure has reached the end of its functional service life. Timing and magnitude of rehabilitation costs will typically have a major effect on the analysis and the overall life cycle cost. Typical practices include: partial-depth and full-depth patching, overlay with asphalt or concrete, treatment with penetrating chemical inhibitors, polymer impregnation, electrochemical chloride removal, and cathodic protection.

USER COSTS

User costs are costs incurred by users of the facility that result from some action (or inaction) related to the structure. On highway facilities, user costs comprise three components: vehicle operating costs, crash costs, and user delay costs. In a technical bulletin on LCCA in pavement design, FHWA recommended values for vehicle travel time ranging from $10 to $24 per hour; for vehicle crash costs, from a low of $151,000 per property damage crash to a high of $1.24 million per fatal crash (*5*). Clearly, on any roadway project where traffic volume is heavy, user costs associated with maintenance, repair, or rehabilitation can add up quickly and become a major cost factor in LCCA. In some instances, user costs can overwhelm both construction and rehabilitation considerations in the analysis.

Historically, user costs have been ignored in making transportation investment decisions. However, public pressure, use of enhanced pavement and bridge management systems, and the desire for improved traffic safety have led to greater awareness and consideration of user costs in LCCA in recent years.

TIMING OF EVENTS AND EXPENDITURES

It is useful in LCCA to graphically represent the timing and magnitude of cash flows in an Expenditure Stream Diagram. The diagram in Figure 7 illustrates the cash flow model used for the example analyses included in the Appendix.

COMPUTING LIFE CYCLE COSTS

If one tries to quantify and consider the uncertainty of all input variables in a life cycle cost analysis, the analysis can become very difficult and time-consuming. Level of complexity and detail should be appropriate for a given project and consistent with the accuracy of estimates. In the examples discussed below, the authors have made the

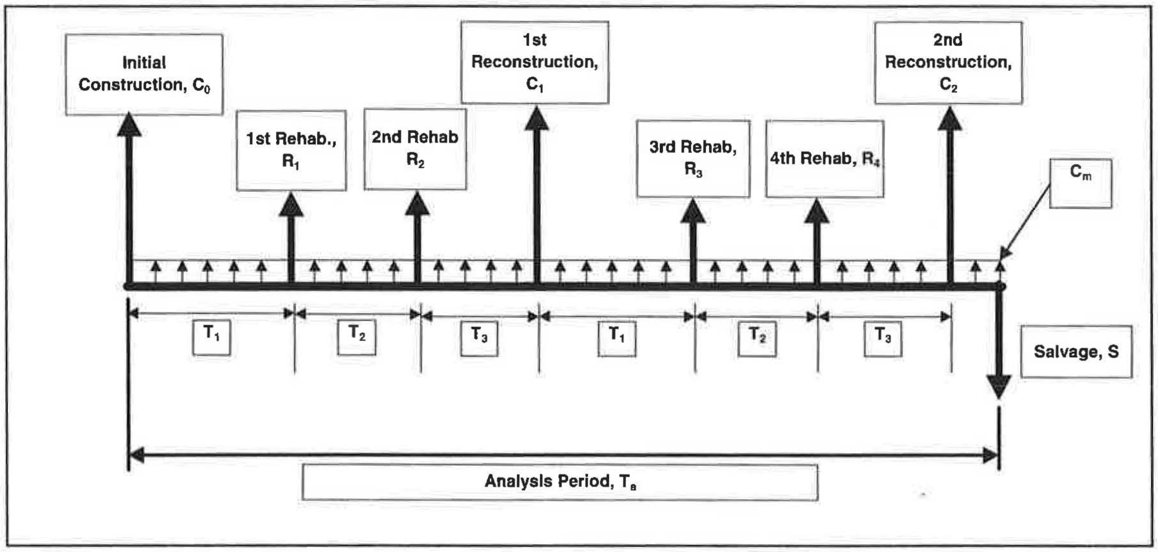


Figure 7: Expenditure stream diagram.

following simplifying assumptions: Consider statistical variability of performance only, not cost factors. Uncertainty of costs can be evaluated through repeated analyses with expected ranges of values. More sophisticated analyses that consider uncertainty of all input parameters are possible using tools such as Monte Carlo simulation and Latin Hypercube Sampling; however, these techniques are beyond the scope of this paper. Refer to Reference 5 for a detailed discussion of these tools.

One obstacle to the use of LCCA is the significant amount of work that is needed to study all feasible alternatives in great detail. To maximize the return on the time invested, it is recommended that a two-step analysis procedure be used. Step 1: narrow alternatives using a "quick and dirty" LCCA, and Step 2: Perform a more detailed evaluation, using sensitivity analysis and parametric study, of finalists.

Discount Rate (i)

LCCA can be done using constant or inflated dollars. It is recommended that constant dollars be used along with a "real" discount rate. Real (as opposed to nominal) discount rates reflect the true time value of money with no inflation premium. The FHWA recommends using a real discount rate in the range of 3 percent to 5 percent (5).

SAMPLE LCCA

A sample life cycle cost analysis comparing several common corrosion protection alternatives is included in the Appendix. A simple spreadsheet was developed to tabulate the various costs associated with each alternative, and to compare each to the base case of doing nothing. Table A1 lists the inputs that were used, and Table A2 the results. The life cycle costs have been computed on the basis of Net Present Value (NPV) according to the equation:

$$\text{Net Present Value} = \text{Initial Cost} + \sum_{k}^{n} \text{Future Costs}_k \left[\frac{1}{(1+i)^{n_k}} \right]$$

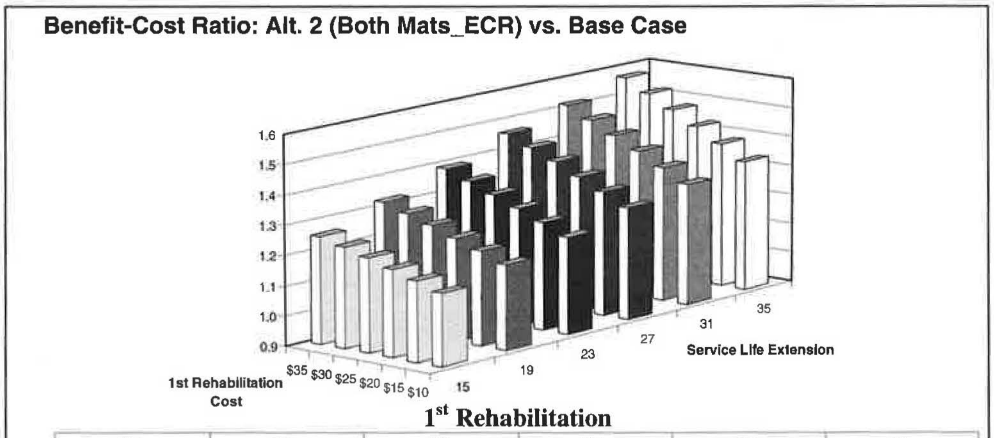
where: n = number of years in future
i = discount rate.

HOW TO USE THE ANALYSIS

To select a corrosion protection strategy, simply computing life cycle costs is of limited benefit. The LCCA can be greatly enhanced by using other supplemental analysis techniques to gain a greater understanding of cost impacts. A Reliability-Based Life Cycle Cost Analysis will yield a range of outcomes with associated probabilities of occurrence. Risk analysis can be used to interpret the results. By making use of sensitivity, parametric, scenario, and break-even analyses, the engineer can optimize the cost effectiveness for the particular conditions and requirements of any given project, and the risk tolerance of the owner.

Sensitivity analysis is a technique for evaluating how "sensitive" the LCCA is to changes in various input factors. *Parametric analysis* can be used to identify the most significant variables. Life cycle costs can then be computed for a range of expected values. If a full reliability-based cost analysis is not possible, one can perform a sensitivity evaluation through multiple analyses using a range of values. A useful technique is to graph the results using a 3-D model for the two most significant inputs. An example of this technique using the sample problem is shown in Figure 8.

Scenario (What if?) Analysis—Once the most significant variables have been identified, one can review results and identify any factors which seem to have a


Benefit-Cost Ratio: Alt. 2 (Both Mats_ECR) vs. Base Case

	$35	$30	$25	$20	$15	$10
□ 15	125.8%	123.7%	121.5%	119.2%	116.7%	114.1%
▨ 19	132.5%	130.0%	127.3%	124.5%	121.6%	118.5%
■ 23	139.0%	136.0%	132.9%	129.6%	126.2%	122.6%
■ 27	146.4%	142.9%	139.3%	135.6%	131.7%	127.6%
▨ 31	151.8%	147.9%	143.8%	139.7%	135.3%	130.8%
□ 35	157.0%	152.7%	148.2%	143.6%	138.9%	134.0%

Figure 8:** **Comparison of net present value of base case (benefit) vs. epoxy-coated rebar-both mats (cost) for a range of rehabilitation costs and service life extension.

disproportionate effect on the analysis. One can then determine if remedial strategies (e.g., tighter quality control, crack repair, preventative maintenance, etc.) will improve system performance. If so, re-compute life cycle costs using the remedial strategy.

Break-even Analysis—It is often useful to utilize a benefit/cost analysis to evaluate the overall effectiveness of an alternative and to test the sensitivity of a key variable. By determining the input value at which benefits (which in this context are equal to the costs associated with the "Do-Nothing" alternative) are equal to the costs associated with the protection alternative—in other words, the Benefit/Cost Ratio equals one. Using the LCCA example for epoxy-coated rebar presented in the Appendix and testing the service life extension parameter, it can be shown that the alternative of epoxy coating the top mat of steel will have equivalent life cycle cost to the "Do-Nothing" alternative when service life extension is only one to two years for the given example. The likelihood of the protection system's actual service life extension exceeding this break-even point is a good benchmark for assessing the overall cost effectiveness of the protection investment.

Finally, the results of these different evaluations should be compared to identify the conditions and/or combinations that lead to each alternative having the lowest life cycle cost (if any.) The selection of the protection system should be made based on the overall likelihood of the lowest-cost scenario actually occurring in practice.

SUMMARY

Clearly, LCCA is not the only consideration in deciding on the design of any particular structure or facility. It must be considered with other "non-economic" factors—politics, budget constraints, competing priorities, and historical preferences—can all take precedence over LCCA at one time or another. However, properly used, life cycle cost analysis is a powerful tool that will facilitate better decision-making, thereby managing risk and optimizing system investment.

Although initial life cycle costing efforts may be somewhat crude and imprecise, continued use over time should hone the analysis and lead to more reliable cost comparisons. If viewed in the proper perspective (i.e., as a decision support tool to be considered with engineering judgement and other factors), even a crude life cycle cost analysis based only on educated professional guesses will usually lead to better decisions than no consideration of future costs at all. As noted by Bondstedt (*6*), Life Cycle Cost Analysis can be, in any particular instance, "specifically wrong", but overall is "generally right." This makes the use of statistically-based life cycle cost analysis an essential prerequisite for a successful bridge management system.

REFERENCES

1. "*AASHTO Guide for Design of Pavement Structures*," American Association of State Highway and Transportation Officials, 1986.
2. Fitch, M.G., Weyers, R.E., and Johnson, S.D., "Determination of the End of Functional Service Life for Concrete Bridge Decks," Transportation Research Board Annual Meeting, Washington, DC, January 22–28, 1995.

3. McDonald, D.B., Pfeifer, D., Krauss, P.D., and Sherman, M., "Corrosion Resistant Reinforcement for Concrete Components," Federal Highway Administration Report, October 1998.

4. Kondratova, I., and Bremner, T.W., "Field and Laboratory Performance of Epoxy-Coated Reinforcement in Cracked and Uncracked Concrete," Transportation Research Board Annual Meeting, Washington, DC, January 12, 1998.

5. Walls III, J., and Smith, M.R., "Life Cycle Cost Analysis in Pavement Design," Federal Highway Administration Interim Technical Bulletin, March 1998.

6. Bondstedt, H.O., "Specifically Wrong—But Generally Right! Actuarial Life Expectancy Projections for Bridges," Prestressed Concrete Association of Pennsylvania, May 1997.

APPENDIX—SAMPLE LIFE CYCLE COST ANALYSIS

The following is an example of a life cycle cost analysis for selecting a corrosion protection system for a reinforced concrete bridge deck. Five different protection strategies are evaluated and compared against a base case of no corrosion protection. These strategies include: epoxy coating one or both mats of reinforcement, stainless steel rebar, galvanized steel rebar, and a combination of High Performance Concrete and Epoxy-Coated Rebar.

The alternatives are compared using an analysis period of 75 years and a discount rate of 4 percent. Rehabilitation costs are estimated to be $25 per square foot, which includes a moderate estimate for user costs. Service life estimates are based on the findings of the previously mentioned FHWA study of corrosion resistant reinforcement (*3*).

Table A1 contains the input values for this sample analysis. Table A2 and Figure A1 show the comparative net present cost for the base case and the five protection alternatives.

Table A1: Life-Cycle Cost Analysis of a Corrosion Protection System: Sample Input Values

Inputs	Base System (no corrosion protection)	Protection System Alternative 1	Protection System Alternative 2	Protection System Alternative 3	Protection System Alternative 4	Protection System Alternative 5
Name--Protection System	Reinforced Concrete Bridge Deck	Top Mat_ECR	Both Mats_ECR	Stainless Steel	HPC & ECR	Galvanized Rebar
Description of Protection Strategy	None	Epoxy coating applied to top mat of deck steel	Epoxy coating applied to both mats of deck steel	316 Stainless Steel Rebar in both mats of deck steel	Special Impermeable Concrete using additives & ECR	Hot-dip galvanized coating applied to all of the rebar
Service Life –Base Case	20 years					
Service Life Extension	N/A	22 years	32 years	56 years	40 years	15 years
Added Cost per Reinforcement Unit	N/A	$0.16 per lb	$0.15 per lb	$2.00 per lb	$0.15 per lb	$0.25 per lb
Reinforcement per Structural Unit	7.0 lbs.	7.0 lbs.	7.0 lbs.	7.0 lbs.	7.0 lbs.	7.0 lbs.
% of Reinforcement Impacted by Protection System	N/A	50%	100%	100%	100%	100%
Added Cost per Concrete Unit	N/A	$.00 per cu. ft.	$.00 per cu. ft.	$.00 per cu. ft.	$.50 per cu. ft.	$.00 per cu. ft.
Concrete per Structural Unit	0.67 cu. ft.	0.67 cu. ft.	0.67 cu. ft.	0.67 cu. ft.	0.67 cu. ft.	0.67 cu. ft.
Total Construction Cost per Structural Unit	$35.00 per sf	$35.53 per sf	$36.05 per sf	$49.00 per sf	$36.39 per sf	$36.75 per sf

Table A2: Corrosion Protection Alternatives: Comparison of Life Cycle Cost

Project: Test Case *Analysis Period = 75 years; Discount Rate = 4%*

Periodic Recurring Expenses	Base Case (Unprotected)			Alt. 1 (Top Mat_ECR)			Alt. 2 (Both Mats_ECR)			Alt. 3 (Stainless Steel)			Alt. 4 (HPC & ECR)			Alt. 5 (Galvanized Rebar)		
Description	Year of Event	Cost	NPV	Year of Event	Cost	NPV	Year of Event	Cost	NPV	Year of Event	Cost	NPV	Year of Event	Cost	NPV	Year of Event	Cost	NPV
Construction	0	$35.00	$35.00	0	$35.53	$35.53	0	$36.05	$36.05	0	$49.00	$49.00	0	$36.39	$36.39	0	$36.75	$36.75
1st repair	20	$25.00	$11.41	42	$25.00	$4.81	52	$25.00	$3.25	75	N/A	$0.00	60	$25.00	$2.38	35	$25.00	$6.34
2nd repair	35	$25.00	$6.34	57	$25.00	$2.67	67	$25.00	$1.81		N/A	$0.00	75	N/A	$0.00	50	$25.00	$3.52
1st reconstruction	50	$42.50	$5.98	72	$43.03	$2.55		N/A	$0.00		N/A	$0.00		N/A	$0.00	65	$44.25	$3.46
1st repair	70	$25.00	$1.61		N/A	$0.00		N/A	$0.00		N/A	$0.00		N/A	$0.00		N/A	$0.00
Salvage, S	75	($26.25)	($1.39)	75	($29.75)	($1.57)	75	($16.33)	($0.86)	75	$0.00	$0.00	75	$0.00	$0.00	75	($17.50)	($0.92)
Total Net Present Value	$58.95			$44.00			$40.25			$49.00			$38.76			$50.42		
As ratio of Base Case	1.00			0.75			0.68			0.83			0.66			0.86		

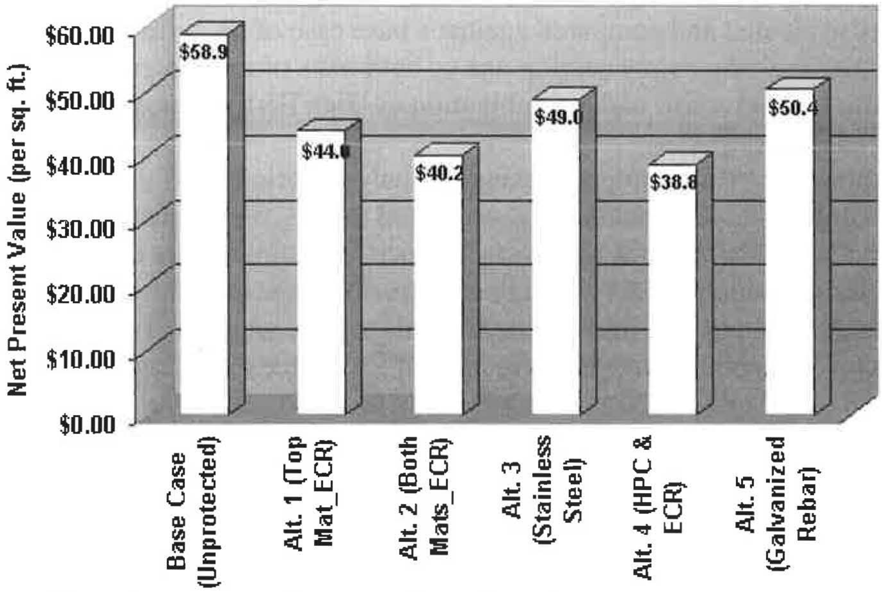


Figure A1: Life cycle cost corrosion protection alternatives: comparison of net present value.